Commercial Engine Architecture Selection in the Presence of Uncertainty and Evolving Requirements

Dr. Bryce Roth,[*] Prof. Dimitri Mavris[†]
Aerospace Systems Design Laboratory, School of Aerospace Engineering
Georgia Institute of Technology, Atlanta, GA 30332-0150

Abstract

The objective of this paper is to discuss a few challenges foreseeable for future aircraft engine designs and briefly survey ongoing research that addresses these challenges. Emphasis is placed on methods for selecting commercial engine architectures. Four fundamental needs are identified and discussed at length: uncertainty in the design process, strategic business decisions in the context of engine design, complexity of future propulsion systems, and integration of new technologies into next-generation products. Probabilistic techniques are suggested as an analytical means to quantify the impact of uncertainty and to allow for uncertainty-mitigating decisions in the design process. Advanced engineering models in conjunction with ideas from complexity theory and game theory are a possible means of addressing the larger strategic business decisions as they pertain to architecture selection. Thermodynamic work potential methods are proposed as a basis for dealing with increased complexity. Finally, the role of technology identification, evaluation, and selection methods in engine technology studies is discussed.

Introduction

It is a fact that in many ways the risk involved in designing, testing, and manufacturing modern gas turbine engines is at least as great today as it has ever been in the past. This statement may at first seem to be counterintuitive because the technology associated with gas turbine engines is more mature today than ever. How then could the risk of building engines today possibly be higher than in the early days when unknown technical difficulties lurked around every corner? The answer is that risk is not simply a function of the probability of failure; it is also a function of what is at stake.

Assume for simplicity that risk is essentially the probability of failure times the cost of failure. Given this definition of risk, it becomes evident why there is significant risk in today's aircraft engine industry. Although it is true that the probability of failure is less for modern designs than for previous generations, it is also true that modern designs are inherently more complicated and much more expensive than previous generations. Thus, the risk of encountering "unknown unknowns" is lower than in the past, but the cost of developing a new design is also higher.

It is likely that the cost of producing new engine designs will continue to escalate at a rate considerably higher than the producer price index for the U.S. industrial sector at large. This trend has been evident since the end of World War II[1] and shows no sign of abatement. If one assumes that the level of risk deemed acceptable by company shareholders is relatively invariant with time, then the probability of failing to meet expectations must continue to decrease in proportion to cost escalation. Consequently, *there is a fundamental need in the aerospace industry to find methods of quantifying and controlling both the probability of failing to meet expectations and the cost associated with failure*.

Likelihood and cost of failure are driven mainly by only a few factors: *uncertainty*, *complexity*, *business environment, and technology*. *Uncertainty* is largely a result of imprecise knowledge of the world around us. It takes the form of design uncertainty, requirements uncertainty, technology uncertainty, etc. *Complexity* is a strong driver on cost, and is also linked to uncertainty due to the fact that increased complexity implies more sophisticated (and generally less understood) products. Business environment plays a strong role in driving design decisions, particularly with regards to acceptable risk and product investment. *Technology* is strongly driven by customer requirements and the need for competitive differentiation, but is also a driver on uncertainty, cost, and complexity. These four fundamental factors will shape the way aircraft engines are designed in the future. This paper discusses how each of these areas presents challenges to future engine designs and gives an overview of techniques that will be available in the future to address these needs.

Uncertainty in Engine Design

As mentioned previously, risk is a strong function of probability of failure, which is in turn strongly dependent on the various sources of uncertainty present during the design process. These sources of uncertainty include: 1) changes in aircraft mission requirements, 2) uncertainty in engine component performance due to analysis tool or experiment fidelity, 3) changes in airframe weight/drag as airframe design evolves from concept to production, 4) changes in regulatory requirements (noise restrictions, emissions regulations, etc.), and 5) uncertainty due to introduction of new/untried technologies.

[*] Research Engineer, Aerospace Systems Design Laboratory (ASDL), School of Aerospace, Georgia Tech. Member, AIAA.

[†] Boeing Professor, Department of Aerospace Engineering, and Director, ASDL. Associate Fellow, AIAA.

One approach to controlling risk is to model uncertainty in the design process via a probabilistic approach that allows explicit calculation of risk associated with every design decision. The benefit of this approach is that it allows one to capitalize on design margin in order to tailor the risk level to that deemed acceptable by investors and/or management. Considerable progress has been made in development of general methods for risk mitigation via probabilistic analysis in the engine size and architecture selection process. Much of this work utilizes state-of-the-art probabilistic analysis algorithms in conjunction with legacy deterministic analysis codes to yield probabilistic descriptions of the impact that uncertainty has on overall engine size, performance, economics, etc. The goal of this work is to create a general method for probabilistic core engine sizing and architecture selection that *encompasses and unifies* all aspects of propulsion system design into a single, comprehensive environment. This section will discuss the fundamental challenges presented by design uncertainty, articulate a global vision for analyzing uncertainty, and discuss relevant research addressing the four sources of uncertainty outlined above.

<u>Fundamental Challenge- Probabilistic Engine Design</u>

The fundamental need for probabilistic core engine sizing and architecture selection methods is illustrated in Fig 1. Consider, for example, the typical situation in which a projected need for an engine in a given thrust class precipitates a response from an engine company. Presume that this engine has a minimum guaranteed thrust and a maximum allowable weight agreed to in advance by the airframe and engine manufacturers. If engine weight and design thrust are plotted as in Fig 1, it forms an "aspiration space" with the vertex of the design requirements being the deterministic design point. However, it frequently happens that the design requirements are not a fixed value, but are instead a "moving target". For instance, as the airframe design evolves, gross weight and/or aerodynamic drag properties may change from original predictions. This may, in turn, cause a change in the desired design thrust at a time when the engine manufacturer has already committed significant capital and resources to designing and building hardware prototypes. Therefore, *from the perspective of the engine manufacturer, the deterministic design point is not deterministic at all, but is better modeled as a probability distribution around the deterministic design point*. This is shown in Fig 1 as a set of dashed probability density contours centered around the deterministic design point.

From a design perspective, the only way to mitigate this uncertainty is to add margins as a hedge against requirement changes. However, this hedge has a real and direct impact on product performance and

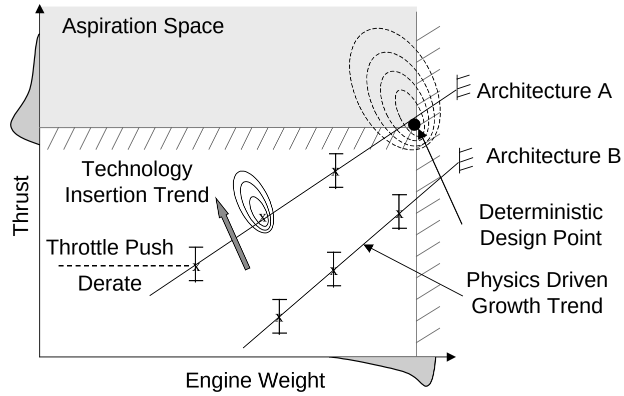

Fig 1 Impact of Internal and External Uncertainties on Core Engine Sizing and Architecture Selection.

profitability - a particularly unacceptable situation in a competitive business environment. Although the example discussed here involves only thrust and engine weight requirements, any real engine is subject to a variety of requirements such as SFC guarantees, acoustic noise guarantees, etc. Consequently, *the requirements aspiration space is n-dimensional and must be described using an n-dimensional joint probability distribution*. This type of uncertainty in top-line design requirements is extremely costly for the all parties involved if not properly addressed. Consequently, there is a clear and present need to find methods to assist in analytically accounting for various sources of uncertainty in requirements.

The prior discussion is only half of the picture relative to propulsion system design uncertainty in that it only discusses uncertainty sources *external* to the design. There are additional sources of uncertainty *internal* to the design that must also be considered. For example, assume that an engine manufacturer intends to field a product in response to the requirement depicted in Fig 1. Presumably, the manufacturer already has an existing product line based on a given engine architecture. For a given engine architecture the design possibilities are limited to a family of engines within the existing core design space, and these will have roughly linear weight increases as thrust increases. This is a natural consequence of the physics of the design, and is depicted by the two lines labeled architecture "A" and "B". Furthermore, a specific engine within a given architecture is denoted by an "x" and growth/derate limits are denoted as error bars centered around a nominal design point.

If the existing architecture cannot meet the requirements (architecture "B"), one can either design a new architecture capable of reaching the design point (architecture "A"), or infuse new technologies that drive the core design space in a direction orthogonal to the physics-driven growth trend (i.e. from "B" towards "A"). However, new technologies are inherently risky

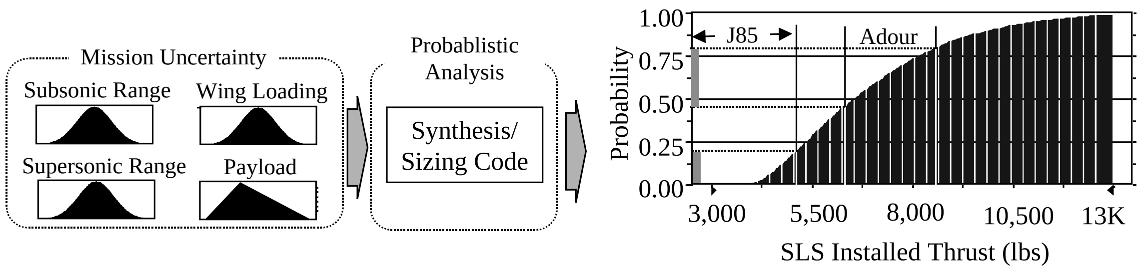

Fig 2 Probabilistic Engine Thrust Sizing (from Ref. 2).

and their performance in a production product can never be precisely known *a priori*. Therefore the exact location of the revised core design space will become "blurred" and must be described probabilistically. Moreover, even if no technologies are introduced, some uncertainty will inevitably remain due to model and analysis tool fidelity limits, manufacturing tolerances, etc. Thus, the exact position of the engine in the requirement space is also a probability distribution, denoted in Fig 1 as a set of solid probability density contours centered around the nominal engine design point.

The probability of a given engine meeting the ultimate requirements is described by the intersection of two joint probability distributions: the requirements uncertainty distribution and the engine design uncertainty distribution. A complete and comprehensive method by which this problem can be solved has *never been formulated*, yet this is precisely what the aircraft engine industry needs to make informed design decisions in today's environment. The next section will describe today's state-of-the-art in engine design uncertainty analysis methods and show typical results obtained.

Uncertainty Analysis State-of-the-Art

A considerable body of research has been published dealing with engine design and requirements uncertainty. Most of this work is directly applicable to the development of a comprehensive engine uncertainty analysis environment. This work includes methods for probabilistic sizing of aircraft engines based on mission requirement uncertainty, probabilistic engine sizing based on aircraft weight and drag uncertainty, and probabilistic engine cycle selection based on uncertainty in engine component performance.

1) Impact of Mission Requirement Uncertainty on Engine Size

A primary source of uncertainty in the engine design process is that due to evolving customer desires (requirements). The state-of-the-art method for analyzing this type of uncertainty is described by Roth and Mavris in Ref. 2. This research focused on developing a method to determine the best (most probable) engine size required for a future unmanned combat aerial vehicle application when operational concepts are still evolving and the mission requirements are ambiguous. The basic probabilistic thrust sizing methodology is illustrated in Fig 2, which shows a scenario where mission parameters such as range and payload are described in terms of a distribution based on current knowledge of what the requirements are ultimately likely to be. This can be translated into distributions on vehicle performance, engine thrust, vehicle weight, etc. using a standard mission analysis code in conjunction with probabilistic analysis techniques. It was shown that probabilistic methods can be used to identify a best (highest probability of success) engine size based on current knowledge of probable mission requirements. This nominal engine size can be used by the engine manufacturer as a starting point for preliminary engine design studies.

2) Impact of Cycle Uncertainty on Vehicle Performance

It often happens that a significant source of uncertainty in the design process is associated with the lack of model fidelity or imprecise knowledge of actual engine component performance. An example of this is described in Ref. 3. In this case, the objective was to probabilistically quantify the impact of uncertainty in engine component performance prediction on vehicle performance. The example consists of an analysis for a large four engine commercial transport aircraft where there is uncertainty on engine component losses.

Typical results from this study are illustrated in Fig 3, which shows the impact of uncertainty in nominal component efficiencies. Note that this figure shows two distributions of aircraft design range, with the distance from tail to tail of each cumulative distribution being on the order of 5% of the vehicle design range. This spread is due to uncertainty in the seven engine component uncertainty parameters shown at the lower left of the figure. Next, if one were to vary the three cycle design parameters shown at the top left within the range defined for the study, the change in the mean design range is on the order of 4% of total design range. Therefore, *the cumulative impact of various uncertainties is on the same order of magnitude as the primary cycle parameters*. The case examined in this example is typical of the situation during the latter stages of preliminary design where the cycle is already

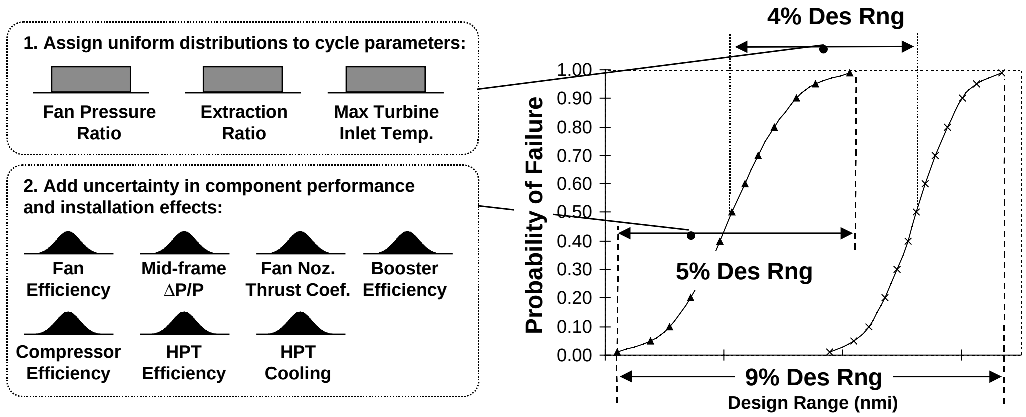

Fig 3 The Impact of Cycle Uncertainty on Vehicle Performance.

well defined, and it is required to have an estimate of engine performance uncertainty before moving into detail design phase.

3) Impact of Aircraft Design Uncertainty on Engine Size

Another source of uncertainty is that due to airframe design evolution. Recent studies have focused on addressing the impact of uncertainty in airframe design estimates on engine thrust sizing for a regional jet. Specifically, this study focused on the impact of vehicle empty weight uncertainty and drag uncertainty on engine thrust size. Typical results are shown in Fig 4, which shows probability distributions on required thrust for three takeoff field length requirements. Actual numbers cannot be shown herein due to the proprietary nature of the information, but *note from this figure that the dispersion of thrust due to airframe uncertainty is on the same order of magnitude as takeoff field length in determining thrust required*. This work will ultimately culminate in a method for analyzing the impact of airframe uncertainty on top-level engine design requirements.

4) Environmental and Regulatory Uncertainties

Environmental and regulatory uncertainties can be a significant source of uncertainty in the engine design process. In particular, uncertainty about future emissions and noise regulations are a source of considerable consternation amongst engine designers. The reason is that most engines, especially commercial engines will see service for an extended period of time. During this time, new environmental regulations, safety regulations etc. could be enacted thereby forcing early product retirement unless these potential scenarios are accounted for adequately. On the other hand, it is not feasible to "gold plate" a design such that it has enough margin to guarantee satisfaction of all possible regulatory changes. This is a logical problem for application of probabilistic analysis methods in a similar vein as described previously. There has been relatively little work to date in developing a method to deal with this type of uncertainty, though work is accelerating in pace.

5) Technology Uncertainty/Risk Analysis Method

A key element needed for the creation of a comprehensive uncertainty analysis environment is a method for evaluating uncertainty due to the introduction of new and untried engine cycle and component technologies. Considerable work is currently ongoing to develop and demonstrate a method for evaluating and selecting optimal suites of technologies, and much of this work will be described later in this paper. However, most of these techniques currently employ a *deterministic* model of technology benefits. In reality, all new technologies imbue some element of risk to the overall system, and this risk effectively degrades technology benefit. One approach to model technology benefit as a *distribution whose standard deviation changes as a function of Technology Readiness Level*. This approach to modeling technology risk has already been demonstrated for aircraft,[4] and should work for modeling propulsion system technology risk as well. However, the unique nature of aircraft propulsion systems and the shear number of possible cycle and component technologies suggests that some modification of the basic approach will be necessary. The bulk of the research on this topic is focused on developing and demonstrating the

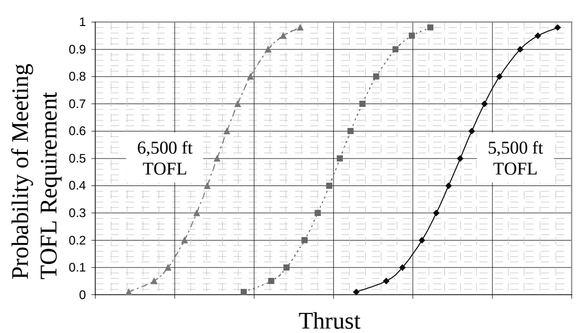

Fig 4 Typical Distributions on Required Thrust Due to Airframe Uncertainty.

requisite technology risk models for propulsion systems.

Joint Probabilistic Decision-Making Methods

The previous five sections have focused on specific sources of uncertainty that must be accounted for in the engine design process. However, each is treated in a monolithic fashion. The challenge is to unify all these separate uncertainty analyses into a single analysis. However, this problem is relatively complicated because the combined problem is inherently multidimensional. Therefore, both the requirements distribution and the design performance distribution must necessarily be represented as joint probability distributions. The intersection of these joint distributions describes the overall probability of a given engine simultaneously meeting all requirements.

Fortunately, a considerable body of research has recently emerged to develop methods for evaluating joint probability distributions. Much of this work is described in Refs. 5, 6 and 7. This work has resulted in the formulation of a generic joint probabilistic decision-making (JPDM) technique that is ideally suited for use in the engine uncertainty analysis environment described in Fig 6. *JPDM is the key enabler that will make a unified uncertainty analysis environment a practical technique instead of a theoretical curiosity*.

Enabling Tools – Probabilistic Cycle Analysis

Currently, an obstacle to implementation of comprehensive engine probabilistic analysis methods is the *lack of established probabilistic analysis capability in current design tools*. Since almost all legacy codes are purely deterministic, the probabilistic analysis must be wrapped abound the deterministic code via linking, shell scripts etc. This is generally a clumsy and time consuming approach to obtain desired results. The obvious solution to this problem is to begin developing basic probabilistic analysis capability within the next generation propulsion analysis codes. Ideally, a basic cycle probabilistic analysis capability would employ advanced probabilistic analysis algorithms such as those described in Refs. 8, 9, & 10 and would allow the user to define a distribution for any cycle model input file. This notional implementation is depicted in Fig 5. The input consists of two types: directives to the probabilistic analysis module, and standard model inputs. The probabilistic module directives would define the analysis type, input distributions, output responses, etc., while the standard inputs would be any model the user desired to analyze. The probabilistic analysis module would then be invoked, and would proceed to automatically run all model cases required to generate the desired probabilistic analysis results. The outputs are then given in the form of distributions on the requested outputs. The probabilistic analysis capability described here could be extended to applications utilizing these modules, giving the

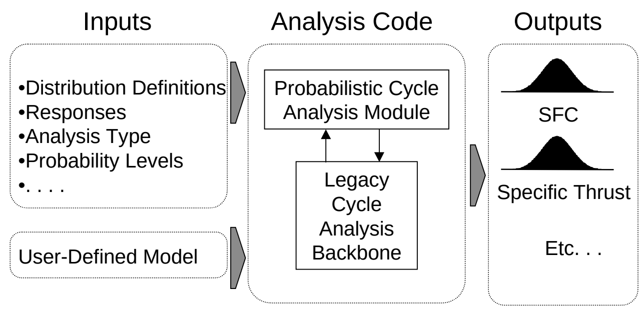

Fig 5 Notional Implementation of Probabilistic Cycle Analysis Capability.

capability to "zoom in" on specific components and apply probabilistic analysis at the detail level, as well.

Strategic Business Environment in Engine Design

The preceding discussion on engine design uncertainty is not the entire story – it considered only the impact of uncertainty on a *single* requirement point without consideration to future growth when the next generation of requirements emerge. However, *the most important choices an engine company makes are those strategic decisions that set core size, engine architecture, etc*. An engine company must make these decisions very carefully because the cost of developing a core architecture is exceedingly high and that single architecture must be capable of meeting not only today's requirements, but also tomorrow's. Therefore, the true problem involves not only requirements and design uncertainty for a single application, but must also consider the broader perspective of a product family and how to strategically position the core architecture to take maximum advantage of both today's and tomorrow's markets.

To better understand this broader perspective and how it interacts with the joint probabilistic requirements/design space previously described, consider the aircraft engine industry as it stands today. Fig 7 shows a plot of design point thrust versus design point SFC for most commercial aircraft engines currently in production. Note that families of engines built around common cores largely fall along a line of points, just as was the case for Fig 1.

If we conceptually think of engine manufacturing as a "game" then Fig 7 is the North American engine manufacturer's "game board" as it stands today.[11] Each point on the plot is an existing engine that represents a single "move" by an engine manufacturer to fulfill an engine requirement. These points are generally clustered around the core design space that represents each company's "turf". At some point in time, each of these points started as a proposed requirement with a joint distribution as described in Fig 1. As the design progressed through time, this distribution stochastically collapsed into a single point, which we see today as a single engine/airframe combination.

Before making any move to put a new point on this "game board", each engine manufacturer must take into consideration not only the uncertainty associated with the present requirements, but also how to best position their product to take advantage of future requirements as they emerge. From an engine manufacturer's viewpoint (and presuming a rational, capitalistic society) the global objective is to dominate the requirements space in such a way as to produce maximum profitability. To do this, one must know the answers to questions such as: "how much design margin is really necessary?", and "how much growth potential should be built into the product?", and "when is a strategic alliance the optimal business strategy?" However, it is very difficult to answer these strategic questions analytically. This section will describe some of the promising research directions that may eventually lead to the development of tools to assist decision makers in answering these questions.

Vision: Probabilistic Core Sizing/Architecture Selection Environment

The needs discussed in the previous section represent a significant research challenge to the propulsion community. Simply modeling and analyzing the combined sources of uncertainty in requirements and design capability is a daunting challenge, and one that has never before been attempted. To include the additional complexity of considering this uncertainty in the context of the larger strategic business environment is even more difficult, and until recently, was so complex as to be nearly intractable.

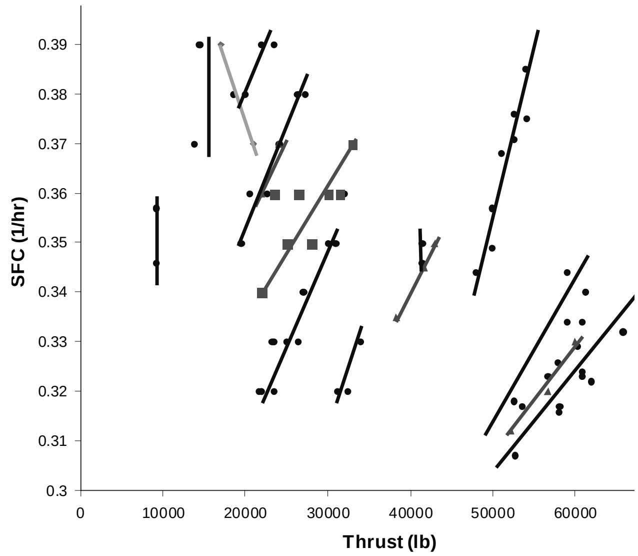

Fig 7 Product Positioning of North American Commercial Aircraft Engines.

Fortunately, there are a variety of new ideas and techniques emerging in the fields of complexity science, game theory, and probability theory that offer promising new approaches to solving these problems. Together, these ideas and theories can be incorporated into a global vision for the development of advanced analysis methods, as shown in Fig 6. The central element of this vision is a global engine uncertainty analysis environment, as described previously. This

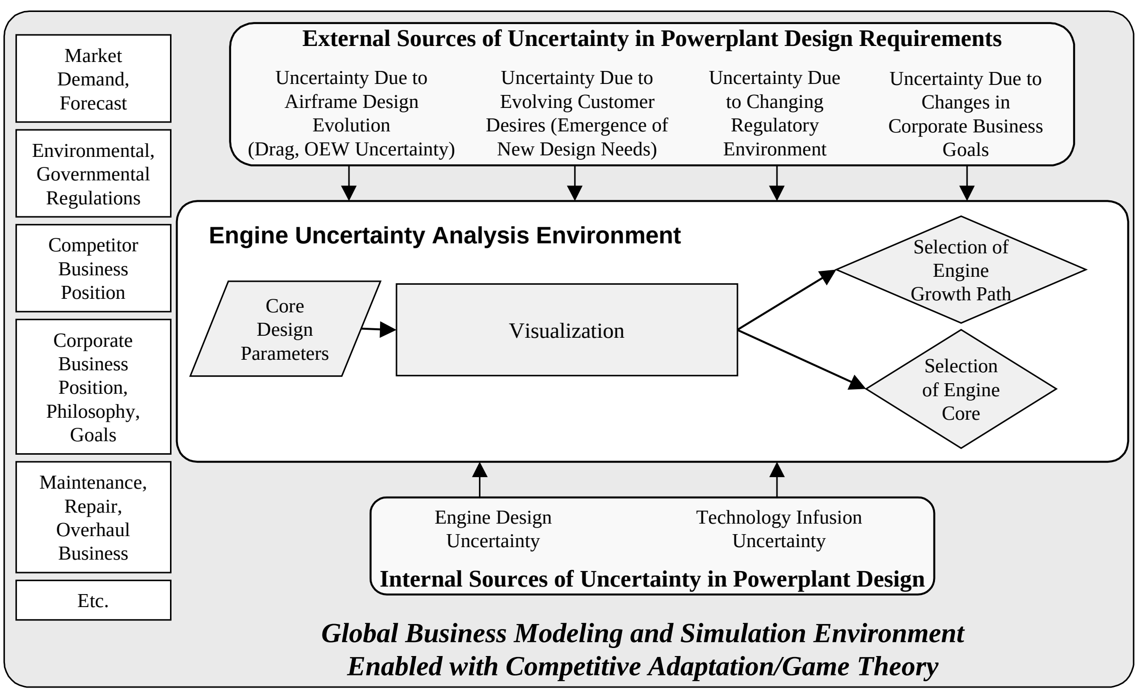

Fig 6 Research Vision Linking Design Uncertainty, Requirements Uncertainty, and Engine Design.

environment would enable the visualization of an engine core design space and the impact that various sources of uncertainty have on it. Such an environment could be used to *analytically* understand the impact that all forms of uncertainty have on a single engine/airframe combination at a given point in its evolution and analyze the probability that the engine will successfully meet the requirements.

The left side of this figure describes the global business modeling and simulation environment that is the analytical backplane used to answer the larger strategic questions referred to earlier. Going back to the game analogy, this portion of the figure describes the "playing field" upon which various strategies and probabilistic scenarios can be "played out" in simulation. This modeling and simulation environment is not sufficient in and of itself to answer the strategic questions posed earlier. Rather, this model must be used in conjunction with some means of generating optimal business strategies such as principles based on the mathematical theory of games. Specifically the concept of competitive adaptation is a key method used in this research to link design decisions to business strategy. Both of these elements are described in detail forthwith.

Modeling and Simulation Environment

A key element needed to make the vision articulated in Fig 6 into a reality is an accurate and comprehensive model for the overall business environment. This model must have sufficient detail to capture the impact of basic engine design parameters on overall business profitability and it must encompass all aspects significant to overall profitability including competitor position, market modeling, maintenance effects, customer value, MRO revenues, spare parts revenues, etc.

The task of creating this model would require a great deal of resources and expert knowledge. Moreover, construction of such a model, though necessary to answer global business questions, is well beyond the scope of academic research. Fortunately, engine manufacturers have already gone to considerable effort to create such models for their own use in evaluating preliminary engine designs.[12] These models are the backbone needed to provide an M&S environment to which the advanced analysis methods discussed herein could be validated.

Game Theory: Linking Business Strategy & Design

The final element required to create the vision articulated previously is a means of analytically selecting engine architectures such that a maximum robustness is achieved with regards to future requirements yet not burden the engine with excessive growth capability. It is in this role that concepts from game theory can be applied to great effect. In a mathematical sense, a game is defined as a model of a competitive situation in which well-defined competitors are striving to meet some game objective. Further, a game has rules for competition. Game theory is a set of mathematical tools and techniques for analyzing these theoretical game models to determine optimal strategy for interested parties.

To understand what role game theory can play as an engine design tool, consider Fig 7. Recall that this figure was described as being analogous to a "game board" on which various engine manufacturers placed their product lines according to their own strategic goals and objectives. Ostensibly, the overarching goal of each manufacturer is to maximize their profitability in the presence of various forms of uncertainty as well as competitor actions. At every point in time, each manufacturer has a spectrum of "moves" available, as illustrated in Fig 8. A complete game then could be theoretically modeled as a series of moves from game start to game end. If one were to map all possible sequences of moves by each competitor from game start to game end, the result would be a decision tree. In theory, if the game model was extremely accurate one could simply evaluate every possible combination of moves to determine the best possible sequence of decisions to guarantee victory. However, a "brute force" search is simply intractable for anything but the simplest of games. This is because the number of branches in this tree increases geometrically with each decision opportunity. Moreover, it is usually impossible to have perfect knowledge about all game parameters, so the additional dimension of uncertainty makes the task even more difficult.

One can think of game theory as a mathematical means of "pruning" this tree such that a limited subset of scenarios can be examined to determine the optimum path. In effect, *game theory can be used as a mathematical means for enumerating decisions available, evaluating options, ruling out those that do not make strategic sense, and determining when alliances are/are not optimal strategies*. Game theory

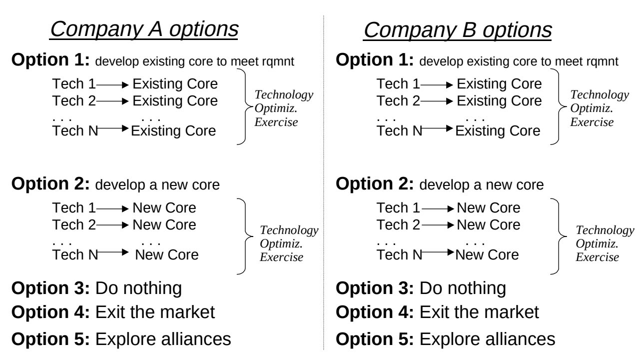

Fig 8 Options Available to Two Engine Manufacturers at Each Stage of a Notional Engine "Game".

can be used to obtain useful results regarding game dynamics even *without* complete information about the real competitive situation. When used in conjunction with the modeling and simulation environment described earlier, game theory could become a mathematical basis for making design decisions in a competitive business environment. *In short, game theory is the bridge linking engineering design decisions with business strategy*.

Complexity in Engine Design

The art and science of vehicle propulsion system design is one of the most complex engineering endeavors undertaken by mankind. All truly good powerplant designs are always a balance between competing aspects of design merit including thermodynamic performance, weight, cost, maintainability, etc. It is precisely this need to balance the many facets of design performance that makes propulsion system design challenging. A necessary prerequisite to achieving this balance is an understanding of the *fundamental nature* of the trades involved and knowledge of the exact cost (in terms of performance, weight, and dollars) of every decision made during the design process. From a propulsion system viewpoint, these trades are typically centered on process efficiencies, or, more to the point, *usage and loss of thermodynamic work potential*.

Currently, *there simply is no rational and organized method in place today to enable the estimation and tracking of work potential usage in vehicle design*, even though work potential is the lifeblood of vehicular motion! The concept of work potential is inextricably linked to the second law of thermodynamics, yet modern design methods make little use of the second law or the work potential concept it suggests. It is the application of work potential concepts to propulsion system design that is the key to enabling calculation of work loss incurred in each thermodynamic process relevant to a vehicle's operation.

The need to accurately calculate loss of flow work potential relative to a thermodynamic ideal has led to interest in methods employing the second law of thermodynamics as a basis for loss estimation.[13,14] This approach is appealing because it provides an unambiguous definition of an ideal against which the actual process can be compared. Thus, whereas conventional analysis methods give information as to the flow of *energy*, a second law-based method enables calculation of *work potential*. This capability will facilitate the creation of analytical models to identify and track all sources of thermodynamic loss in an entire vehicle or subsystem. Such an approach would make it possible to estimate the *absolute* loss associated with each loss mechanism in terms of a *single figure of merit* (FoM) applicable to *all* vehicle components and processes.

Potential Impact and Applications

Work potential methods are taken here to mean a class of methods employing the first and second laws of thermodynamics to enable analytical calculation of the maximum work theoretically available from thermodynamic processes. The concept of work potential is naturally suited to be an integrating framework that will provide a framework for the many trades that must occur between the various components of tomorrow's increasingly complex propulsion systems. The potential applications for these techniques towards simplifying and improving the design process are only now beginning to be explored. This section will point out a few of the features that make work potential methods useful in propulsion system design and, where possible, illustrate their application by way of example.

The Limits of Design Perfection

One of the most basic advantages of viewing engine aerothermodynamic performance in terms of work potential is that it inherently focuses all attention on what the *absolute magnitude* of loss is and unambiguously identifies the source of each loss. It becomes immediately obvious using the work potential method how much improvement is possible and how close the actual system is to ideal. Moreover, it is immediately evident which components of the system are causing the most loss, thereby attracting attention to those areas where the most improvement is possible. In short, *the concept of work potential is as fundamental to defining the limits of engine design as Carnot cycle is to defining the limits of thermodynamic performance*.

This notion is illustrated in Fig 9 for the Northrop F-5E fighter aircraft. This figure depicts the breakdown of total exergy usage throughout the F-5E's design mission, a subsonic area intercept of 225 nmi radius. In flying this mission, the F-5E consumes 4,400 lbs. of JP-8. This JP-8 has some work potential inherently stored in it, which is released by combustion in the engine. Of the work potential (exergy) initially stored in the fuel, the left side of Fig 9 shows that roughly 90% of it emerges as losses in the propulsion system. The top right of this figure shows that the vast majority of these propulsive losses consist of exhaust heat, irreversible combustion, and residual kinetic energy of the jet efflux left in the wake of the vehicle. The remaining 10% of the exergy is converted into thrust work and used to overcome vehicle drag (lower right). This is a perspective that couches the problem in raw and fundamental terms: *from a thermodynamic perspective, the vast majority of losses in most aerospace vehicles occur in the propulsion system*. It is abundantly clear based on this figure that there is much to be gained by concentrating on reducing these propulsive losses.

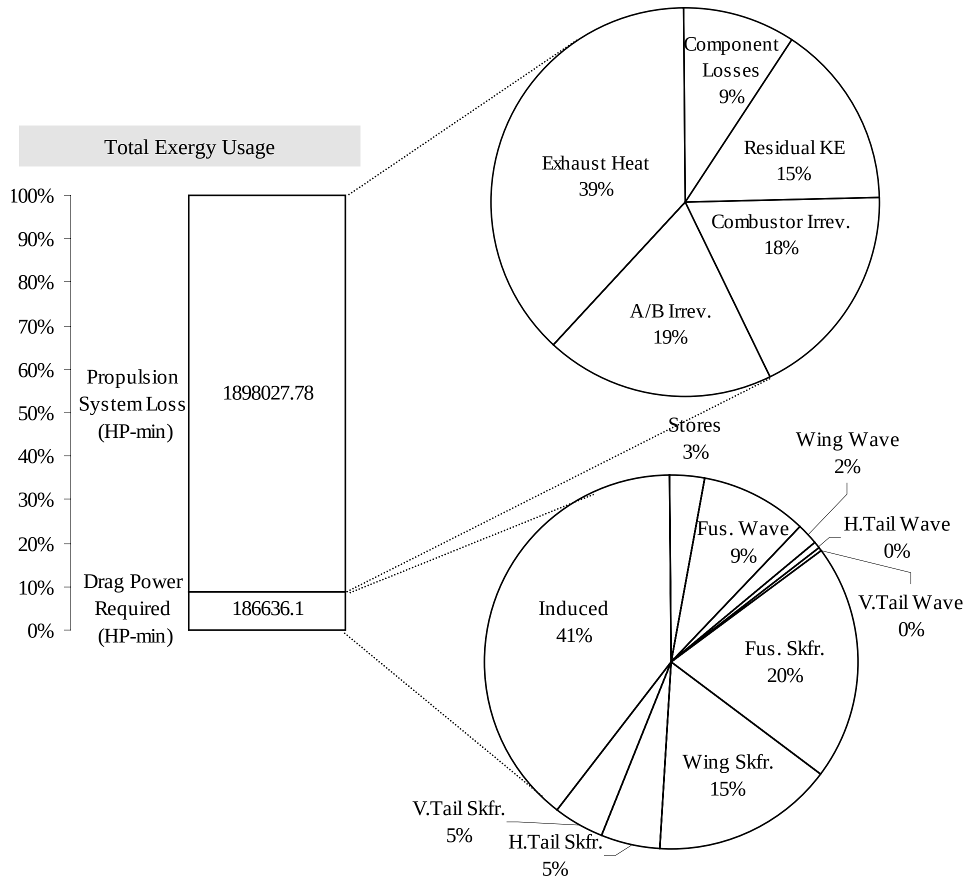

Fig 9 Total Exergy Usage During F-5E Subsonic Area Intercept Mission.

A "Universal Currency" for Vehicle Design

An advantage that thermodynamic work potential has, as a measure of propulsion system performance is that work potential is a fundamental quantity directly related to the physics of the problem. In fact, work potential is *thermodynamic property* of a substance, in the same sense that enthalpy, entropy, etc. are thermodynamic properties. Consequently, work potential has the same definition for all thermodynamic processes, regardless of the physical component. In other words, a loss of 1 unit of work potential in a compressor is the same as a loss of 1 unit of work potential in the combustor, turbine, air conditioning packs, radar, and *all* other systems. This is in contrast to the conventional system of component efficiencies wherein 1 point of compressor efficiency is *not* equivalent to 1 point of turbine efficiency, etc. This situation is punctuated in Table I, which lists an abbreviated subset of the component efficiencies typically used in aircraft engines. Each component efficiency is unique and cannot be directly compared to any other efficiency. However, as this table shows, the work potential viewpoint does not suffer any such handicap: all component losses can be directly compared to one another on an "apples to apples" basis. It therefore seems logical to presume that the concept of work potential can be used as a common figure of merit (FoM) for judging the absolute value of losses compared amongst disparate components and thermodynamic processes. Moreover, this feature is even more useful as a means of evaluating revolutionary propulsive concepts for which there may not even be a standard definition of efficiency available. In short, *just as a viable country must have a common currency to facilitate commerce and trade, so must aerospace vehicle design have a common currency to facilitate design trades*. Thermodynamic work potential is the "universal currency" of aerothermodynamic performance that is needed for aerospace vehicle design.

A Framework for Understanding Technology Impact

Integration and evaluation of advanced technology in tomorrow's highly complex and integrated vehicles is one of the most formidable tasks facing designers today. Technology integration is inherently a multidisciplinary problem requiring tremendous depth and breadth of knowledge to accomplish. Moreover, it is difficult to ascertain the true benefits of any individual technology when employed as part of a suite of advanced technologies installed in an advanced

Table I Comparison of Commonly Used Engine Efficiencies to Their Equivilent Work Potential FoMs.

Component	***Classical Efficiency***	***Work Potential Equivalent***
Inlet	$\text{Inlet Pressure Recovery} \equiv \dfrac{\text{Inlet Discharge Stagnation Pressure}}{\text{Freestream Stagnation Pressure}}$	Loss in Work Potential
Compressor	$\text{Compressor Efficiency} \equiv \dfrac{\text{Ideal Compression Work Required}}{\text{Actual Compression Work Required}}$	Loss in Work Potential
Combustor	$\text{Combustion Efficiency} \equiv \dfrac{\text{Actual Combustion Heat Release}}{\text{Ideal Combustion Heat Release}}$	Loss in Work Potential
Combustor	$\text{Combustor Pressure Loss} \equiv \dfrac{\text{Combustor Discharge Pressure}}{\text{Combustor Inlet Pressure}}$	Loss in Work Potential
Turbine	$\text{Turbine Efficiency} \equiv \dfrac{\text{Actual Expansion Work Produced}}{\text{Ideal Expansion Work Produced}}$	Loss in Work Potential
Nozzle	$\text{Nozzle Thrust Coefficient} \equiv \dfrac{\text{Actual Jet Thrust}}{\text{Ideal Jet Thrust}}$	Loss in Work Potential

design or concept demonstrator. This is due to interactions amongst the technologies and because there is seldom a common figure of merit that captures all aspects of how a technology impacts the entire system.

Work potential methods have considerable ability to facilitate evaluation and selection of those technologies that impact vehicle aero-thermodynamic performance and/or weight. This is because work potential methods give direct input as to how and where a given technology impacts system aerothermo performance. The result is an understanding of the *underlying effect* that the technology has on each functional component as opposed to a description of the *net effect* at the system level.

Analysis of Unconventional/Revolutionary Propulsion Systems

In an absolute sense, the most significant sources of loss in work potential occur in the propulsion system. This point is punctuated by Fig 9, which shows that *90%* of the work potential initially available in the fuel is lost in the propulsion system of the Northrop F-5E. This trend is typical for vehicles of all types (land, sea, or air): losses in the propulsion system dominate overall vehicle efficiency. Therefore, there is a strong incentive to develop more efficient propulsion systems that are better able to utilize the work potential inherent in the fuel, the ultimate goal being drastic reductions in fuel consumption on the order of 75% less than today's state-of-the-art.

The majority of the losses occurring in modern propulsion systems are not due to the design of the components themselves, but are rather due to the nature of the basic propulsive cycle they employ. For instance, Fig 9 shows that the dominant sources of loss in the F-5E are irreversible combustion, exhaust heat, and exhaust residual kinetic energy. These are all due to the fundamental cycle, and can only be decreased by increasing cycle pressure ratio & turbine inlet temperature, and lowering engine pressure ratio. Gas turbine technology has made tremendous strides in the past three decades, but even so, there is still much room for improvement. However, each incremental improvement is significantly more difficult than the preceding improvement, and many believe that we are reaching the point of diminishing marginal returns for most modern (Brayton based) propulsion technologies. Therefore, there is a strong impetus to examine revolutionary new propulsion technologies that are not hindered by the fundamental limits present in established technologies.

By definition, a revolutionary technology is one that is not well known. Therefore, there are not likely to be any established performance FoMs (the "component efficiencies") available, and it may not even be known where the greatest losses occur in the propulsive cycle. It therefore makes sense to quantify design performance of revolutionary propulsive technologies using an intuitive performance FoM that is *directly comparable to known propulsion systems*. The work potential FoM fits this description: it can be applied to the analysis of *any* propulsion system, it is intuitive, and it facilitates "apples-to-apples" comparisons between disparate propulsive concepts.

Technology in Engine Design

The final "grand challenge" that must be faced by future designers is that presented by engine technologies and their integration into next generation systems. This is intimately related to uncertainty and complexity, as new technologies are by definition untried and therefore somewhat uncertain. Moreover, advanced technologies are usually more complex than the older designs they replace. The fundamental challenge is to determine which technologies yield the best compromise amongst the various conflicting design objectives while simultaneously having the least possible development and risk to realize in a commercial product.

A great deal of research effort has gone into the development of methods to address this type of problem. One of the most prominent is the Technology Identification, Evaluation, and Selection (TIES)

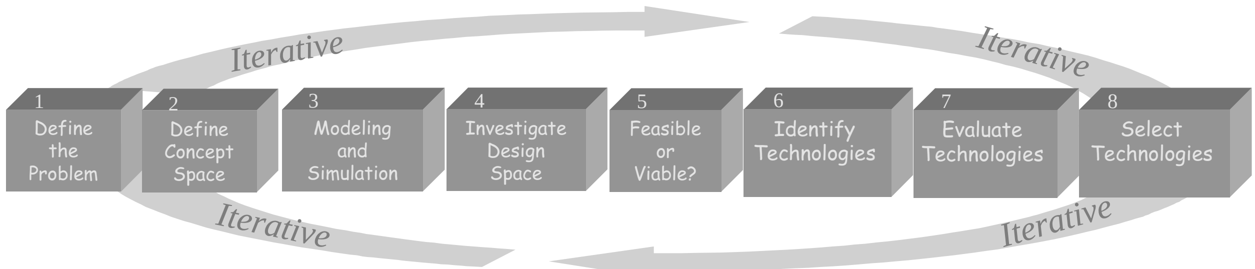

Fig 10 TIES Analysis Process (From Ref. 16).

methodology developed for the Office of Naval Research.[15] The chief strength of this method is that it allows rapid identification and evaluation of technology concepts, provides a risk/reward ranking of technology development options, and provides a compromise between analysis accuracy and time/cost to conduct preliminary-level technology assessments.

A flowchart of the basic TIES method is given in Fig 10. Note that the TIES method spans the entire technology selection process starting with identification of the need for new technologies and ends in technology selection. TIES is also suitable for the inverse problem where the objective is to find how much technology impact is required to meet a given goal. The fundamental premise of the TIES method is the notion that all technologies can be modeled as deltas in a few key technology metrics. This is what allows the TIES technique to strike a balance between accuracy and speed. The method and its underlying principles are described in detail in Ref. 16.

This technique was recently demonstrated for a engine technology selection problem involving 40 technologies.[17] Since classical gradient-based optimization techniques do not work well for this class of problem (because technology selection is essentially a combinatorial optimization problem), much of the recent development work in this area has focused on applying advanced combinatorial optimization techniques. In particular, genetic algorithms (GAs) have proven very useful for solving this type of problem and are used for this purpose in Ref. 17.

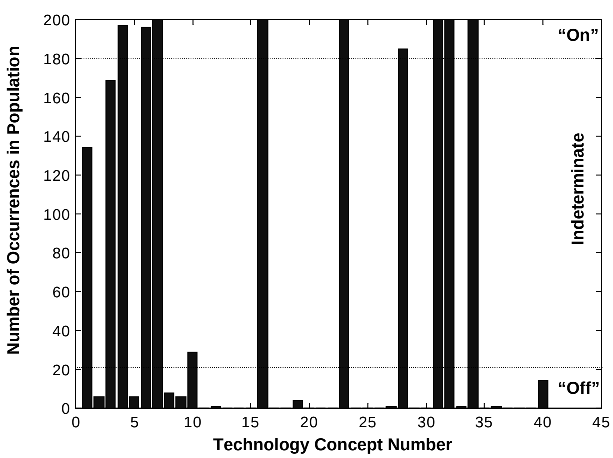

Fig 11 Typical Optimal Engine Technology Solution Set (From Ref. 17).

Typical GA technology optimization results are shown in Fig 11. This figure shows a commercial engine technology optimization problem using a GA-enabled TIES technique to select technologies. The abscissa shows 40 technologies, labeled numbers 1-40. The ordinate shows the number of times each technology occurs in the last (i.e. converged) generation of a 200-member population. Therefore, a technology that is universally present in the converged population would occur 200 times. Conversely, a technology that was not conducive to the optimization objectives would appear very rarely in the evolved population. Fig 11 shows that the technologies satisfying the optimization objectives are numbers 4, 6, 7, 16, 23, 31, 32, and 34. All other technologies do not provide sufficient benefit to outweigh their development cost and risk.

Conclusions

This paper has discussed the need to develop a method that assists decision-makers in answering global questions regarding the basic architecture and core size/growth path decisions. This method must include the impact of all sources of uncertainty, and must also incorporate some model of the global business environment that captures the impact of all business aspects pertinent to determining ultimate profitability as a function of basic engine design decisions. It must incorporate a general framework that will allow future designers to easily and quickly comprehend the complex interactions amongst system components. Finally, it will require the application of advanced methods to find the best technology strategy based on a given business model.

This paper has presented several areas of research that are key elements needed to meet these needs. A general methodology was formulated for selecting engine architecture based on uncertainty in airframe characteristics, engine attributes, and the aircraft mission. It also allows the effect of technology infusion in the engine or aircraft to be explored in terms of its impact on the engine design space. Ultimately, this method will allow engine and airframe manufacturers to make informed decisions on the requirements for a new core engine design. This decision-making ability may be enhanced in the future by the application of techniques such as work potential, joint probabilistic decision making (JPDM), and game theory.

Acknowledgements

We would like to thank the Office of Naval Research for providing funding to do much of the basic research described herein under grant N00014-97-1-0783. We would also like to thank our industrial sponsor, GE Aircraft Engines, for their support on portions of this work. Specifically, thanks are due to Mr. Jim Younghans for his guidance throughout.

References

[1] Bright, C.D., *The Jet Makers*, Regents Press of Kansas, Lawrence, KA, 1978.

[2] Roth, B.A., Mavris, D.N., "A Probabilistic Approach to UCAV Engine Sizing," Presented at the 1998 Joint Propulsion Conference, Cleveland, Oh, July, 1998, AIAA98-3264.

[3] Mavris, D.N., Macsotai, N.I., Roth, B.A., "A Probabilistic Design Methodology for Commercial Aircraft Engine Cycle Selection," 1998 World Aviation Congress and Exposition, Anaheim, CA, September 28-30, 1998. SAE-985510.

[4] Kirby, M.R., Mavris, D.N., "Forecasting Technology Uncertainty in Preliminary Aircraft Design," SAE99-01-5631.

[5] Bandte, O., *A Probabilistic Multi-Criteria Decision Making Technique for Conceptual and Preliminary Aerospace Systems Design*, Ph.D. Thesis, Georgia Institute of Technology, September, 2000.

[6] Mavris, D.N., Bandte, O., DeLaurentis, D.A., "Determination of System Feasibility and Viability Employing a Joint Probabilistic Formulation," AIAA-99-0183.

[7] Bandte, O., Mavris, D.N., DeLaurentis, D.A., "Viable Designs Through a Joint Probabilistic Technique," SAE1999-01-5623.

[8] Wu, Y.T., "Computational Methods for Efficient Structural Reliability and Reliability Sensitivity Analysis," *AIAA Journal*, Vol. 32, No. 8, August 1994.

[9] Wu, Y.T., "Methods for Efficient Probabilistic Analysis of Systems With Large Number of Random Variables," AIAA-98-4908.

[10] Wu, Y.T., Millwater, H.R., Cruse, T.A., "Advanced Probabilistic Structural Analysis Method for Implicit Performance Functions," *AIAA Journal*, Vol. 28, No. 9, September 1990.

[11] "2001 Source Book," *Aviation Week and Space Technology*, McGraw Hill, New York, January 8, 2001.

[12] Younghans, J.l., et al, "Preliminary Design of Low Cost Propulsion Systems Using Next Generation Cost Modeling Techniques," *J. of Eng. For Gas Turbines and Power*, Vol. 121, January 1999.

[13] Roth, B.A., Mavris, D.N., "A Comparison of Thermodynamic Loss Models Suitable for Gas Turbine Propulsion," *J. of Propulsion and Power*, Mar-Apr 2001, Vol 17, No. 2, PP324-332.

[14] Roth, B.A., *A Theoretical Treatment of Technical Risk in Modern Propulsion System Design*, PhD Thesis, Georgia Institute of Technology, Atlanta, GA, Mar., 2000.

[15] Kirby, M.R., Mavris, D.N., "A Method for Technology Selection Based on Benefit, Available Schedule, and Budget Resources," Presented at the 2000 World Aviation Congress, San Diego, CA, Oct. 10-12, 2000, SAE2000-01-5563.

[16] Kirby, M.R., *A Method for Technology Identification, Evaluation, and Selection in Conceptual and Preliminary Aircraft Design*, Ph.D. Thesis, Georgia Institute of Technology, March 2001.

[17] Roth, B.A., German, B.J., Mavris, D.N., Macsotai, N.I., "Adaptive Selection of Engine Technology Solution Sets from a Large Combinatorial Space," 2001 Joint Propulsion Conference, Salt Lake City, UT, AIAA2001-3208.